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## Scale Factor Study for 1:30 Local Scour Model

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**PURPOSE:** This Coastal and Hydraulics Engineering Technical Note (CHETN) contains a description of the process used to generate a scale factor for a 1:30 physical model of the Burlington Northern Santa Fe Railway Company (BNSF) railway crossing on the Santa Ana River near Corona, CA. Data from the scale factor study provide an adjustment for applying documented scour behavior from round piers to a non-typical parallelogram tapered pier and proposed pier nose extension found at the BNSF Bridge. The scale factor establishes the worst-case scour depth for the current bridge configuration and the proposed pier nose extension.

**INTRODUCTION:** Extensive research has been conducted for local scour around typical pier shapes (e.g., round, square, diamond) with the most commonly studied shape being the round pier. Multiple studies for round piers have been conducted in flumes as well as field observations (Breusers et al. 1977; Chiew 1984; Kothyari et al. 1992; HEC-18 2012; Melville and Chiew 1999; Lee and Sturm 2009; Mia and Nago 2003; Mueller and Wagner 2005). Multiple predictive equations have been formulated from pier scour studies to provide conservative estimates of maximum scour depth (Laursen and Toch 1956; Shen et al. 1969; Breusers et al. 1977; Jain and Fischer 1979; Melville and Sutherland 1988; Lim 1997; Heza et al. 2007; HEC-18 2012). The maximum scour depth is then applied in the design of footing depths for bridge piers. The most commonly used equation for calculating maximum scour depth is the HEC-18 equation, but it is only applicable for typical pier shapes (HEC-18 2012). When non-typical complex pier shapes are used, such as those illustrated in Figure 1, the recommended practice is to conduct a physical model study (HEC-18 2012). Thus, the application of historic field and flume data along with the HEC-18 equation is replaced with measurements made in a physical model.

Prior to construction and testing of the 1:30 general physical model of the BNSF Bridge, model scale conversion ratios, domain bounds, and the overall configuration were established. In addition to the typical model scale conversion ratios, a new model scale factor ratio specific to the model bed material (uniformly graded medium sand) at 1:30 scale was formulated for local scour at round piers. The model scale factor ratio for local scour was formulated in this scale test and established a conservative adjustment for local scour depth for the atypical pier configuration used in the general model.

As formulated here, the scale factor provides a scour depth adjustment comprised of two components. The first component is scale effects due to model issues and is the primary focus of this effort. The second component addresses concerns regarding the safety factor formulated in the HEC-18 equation. In this effort, a scale factor range was produced to provide a minimum and maximum for local pier scour at the BNSF railway piers (Figure 1) in the 1:30 general physical model.

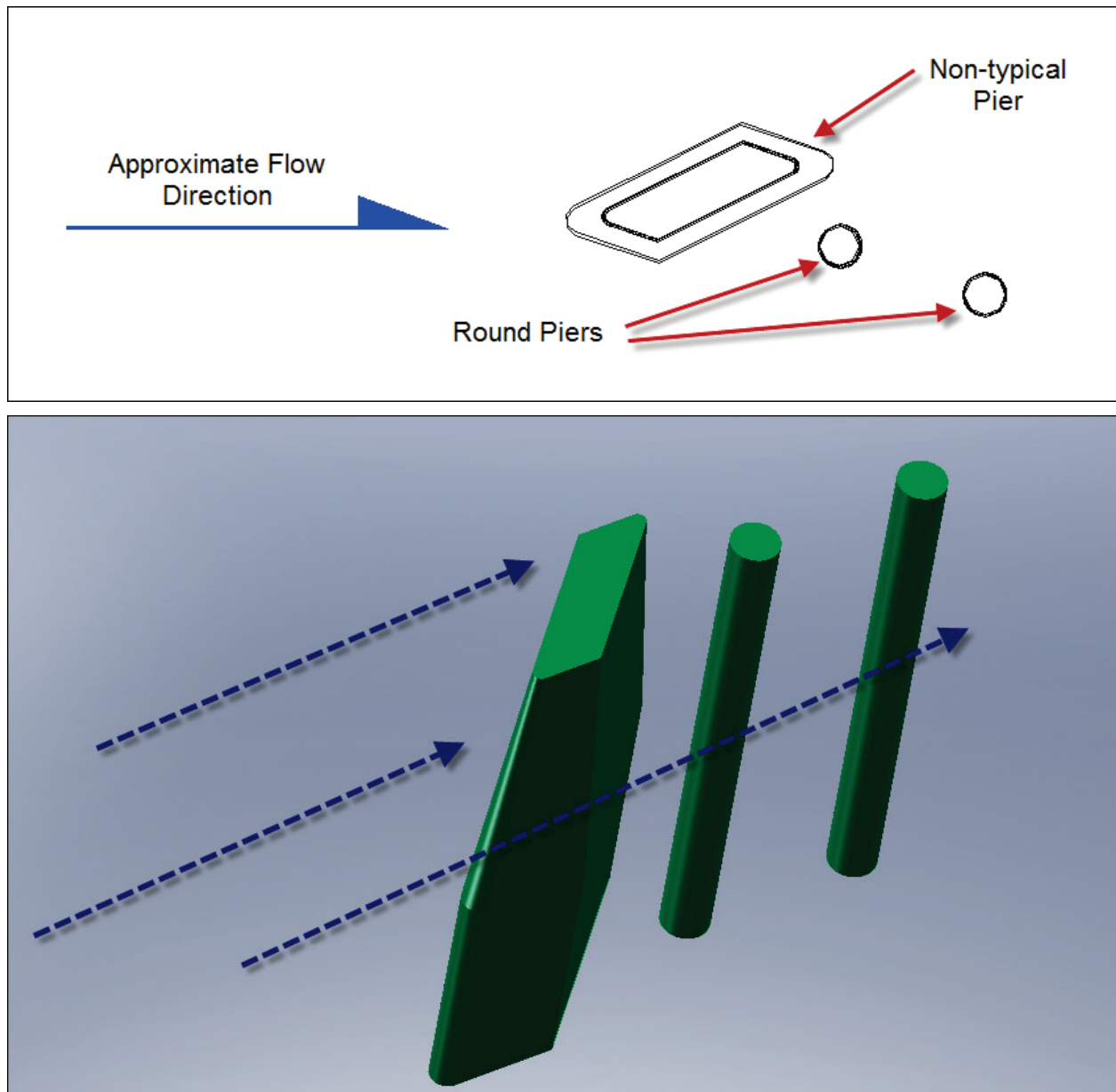


Figure 1. Typical configuration of pier sets at the BNSF railroad bridge, plan view above and three-dimensional (3D) rendering below.

**PROCESS AND SETUP:** In order to incorporate the peer-reviewed data from the literature with the nontypical bridge piers found at the BNSF Bridge (Figure 1), a scale test was formulated. Fundamentally, the scale test is a comparison between the HEC-18 equation for round piers and the trapezoidal shaped piers found at the BNSF Bridge. The comparison is achieved by setting up a flume test with both typical round piers and the pier sets found at the BNSF Bridge (Figure 2).

The scale test was configured with the same sediment, uniformly graded sand with a  $D_{50}$  of 0.25 mm (Figure 3) and scale length ratio of 1:30 used in the general physical model. A flat test section, approximately 32 ft long and 34–45 ft wide, was molded to a uniform elevation. Stilling

well gages were placed upstream and downstream of the piers. The stilling well gages provide the slope and depth of the flow during the tests. The round piers were spaced 11.25 ft apart. Then the two pier sets were located between the round piers but 12 ft downstream (Figure 2). This provided an approach and exit length of 10 ft. The spacing of these piers was sufficiently large enough to prevent any interaction of the currents between pier sets.



Figure 2. Test configuration of round piers and pier sets for Test 5.

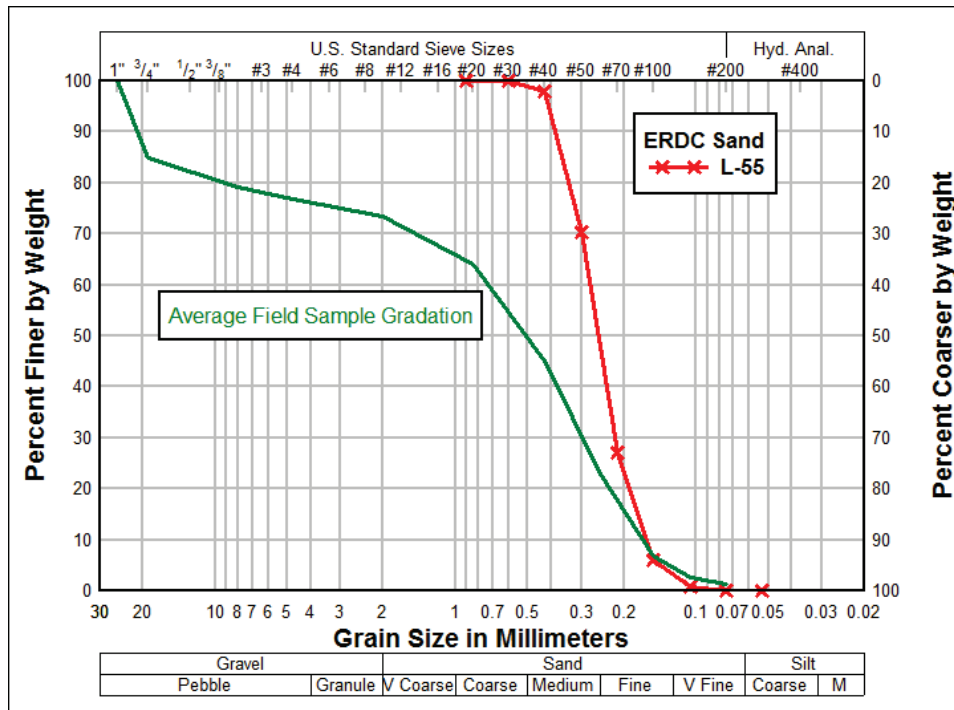


Figure 3. Test and prototype material gradations.

Boundary conditions were controlled with a gate valve and a tailwater lift gate. The head tank and tail tank were located 84 ft upstream and downstream of the test section respectively. Discharge into the model came from three recirculation pumps with a total capacity of

approximately 12.5 ft<sup>3</sup>/sec. Flow uniformity was checked with an electromagnetic velocity meter and adjusted with upstream baffle blocks. The total discharge was measured by reading the differential from a manometer across a venturi meter and verified with a total discharge calculation from the flow uniformity checks. The water surface elevation was controlled with the adjustable lift gate at the downstream end of the flume.

The tests' configuration established and maintained clear-water scour conditions, which produce consistent test results. Prior to each test, the tailgate was raised, and the test section was flooded. Once flooded, the flow was adjusted to the desired discharge. Upon setting the discharge, the tailgate was lowered to the chosen height. The height of the gate set the pre-determined flow depth at the piers. The depth was typical of what is expected at prototype scale. The average run time for each test was approximately 18 hours of model time. At various times during testing, the local scour depth was surveyed. Tests were run until the quasi-equilibrium scour depth was reached.

Five tests were conducted to measure the local scour at the piers. Tests 1 and 2 had three round piers. Test 3 and 4 had three round piers and two pier set configurations like those found at the BNSF Bridge. Test 5 only had two round piers since a higher unit discharge was required and achieved by narrowing the flume from 45 to 34 ft. These five tests provided 14 scour depth data points for the round piers and 6 for the BNSF pier sets. Collected data included approach velocities and depths, discharge, water-surface slope, and maximum-scour depth. From these five tests, three different flow depths (reported here at prototype scale) were evaluated: 9, 14, and 17 ft. The depth selection was based on mean flow depths expected at prototype. For each test, clear-water scour conditions were generated. At the end of each simulation, the observed scour rates were essentially zero, indicating that a quasi-equilibrium condition had been attained. Sediment transport into the test section was negligible; however, small perturbations upstream (from dye insertion or velocity measurements) caused ripples to form. The measured scour depth is believed to be reasonable for quantitative comparisons between the evaluated configurations. Note that the results are reported in prototype dimensions; thus, the data were scaled undistorted by the length scale ratio of 1:30. Scaling to prototype was done in order to make direct comparisons between the model results and the actual site.

**RESULTS AND DISCUSSION:** Test results for round piers showed scour depth increasing as flow depth increased (Table 1 and Figure 4). The flow depth and scour depth correlation of 0.80 for the tests is illustrated in Figure 4 and is expected (Laursen 1952). As stated in ASCE Manual 54 (Vanoni 2006, page 38), "the equilibrium (scour) depth appears to depend only on the initial depth of flow and to be independent of both the mean velocity and the sediment characteristics." Thus, the greatest scour depth for these tests occurred with the 16.9 ft flow depth, and the lowest scour depth occurred with the 9.1 ft flow depth with 6.7 and 3.4 ft of scour, respectively (Table 1 and Figure 4).

For the selection of the scale factor, it was decided to use the maximum and minimum from the five tests shown in Table 1, thereby bracketing the 14 scour depth measurements into a scale factor range that will provide the most and least conservative scour depth estimates. Figure 4 shows the results from all the tests.

Table 1. Collected data for round pier tests.							
Collected Data from Round Pier Tests						HEC-18 Scour Depth	Scale Factor
	Pier Location	Flow Depth, ft	Scour Depth, ft	Approach Velocity, ft/s	Unit Discharge, ft <sup>3</sup> /ft		
Test 1	Left	14.7	4.90	2.92	42.99	7.62	1.55
	Center	14.7	5.62	2.87	42.25	7.56	1.35
	Right	14.7	4.76	2.94	43.31	7.64	1.61
Test 2	Left	9.1	4.18	3.18	28.90	7.41	1.77
	Center	9.1	4.15	3.28	29.75	7.50	1.81
	Right	9.1	3.40	3.19	28.94	7.41	2.18
Test 3	Left	9.4	4.66	3.02	28.34	7.27	1.56
	Center	9.4	4.81	3.11	29.22	7.37	1.53
	Right	9.4	4.60	3.02	28.38	7.27	1.58
Test 4	Left	13.8	4.80	3.32	45.79	7.98	1.66
	Center	13.8	5.70	3.44	47.42	8.10	1.42
	Right	13.8	4.80	3.33	45.90	7.99	1.66
Test 5	Left	16.9	6.00	3.58	60.37	8.47	1.41
	Center	16.9	6.70	3.67	61.80	8.56	1.28

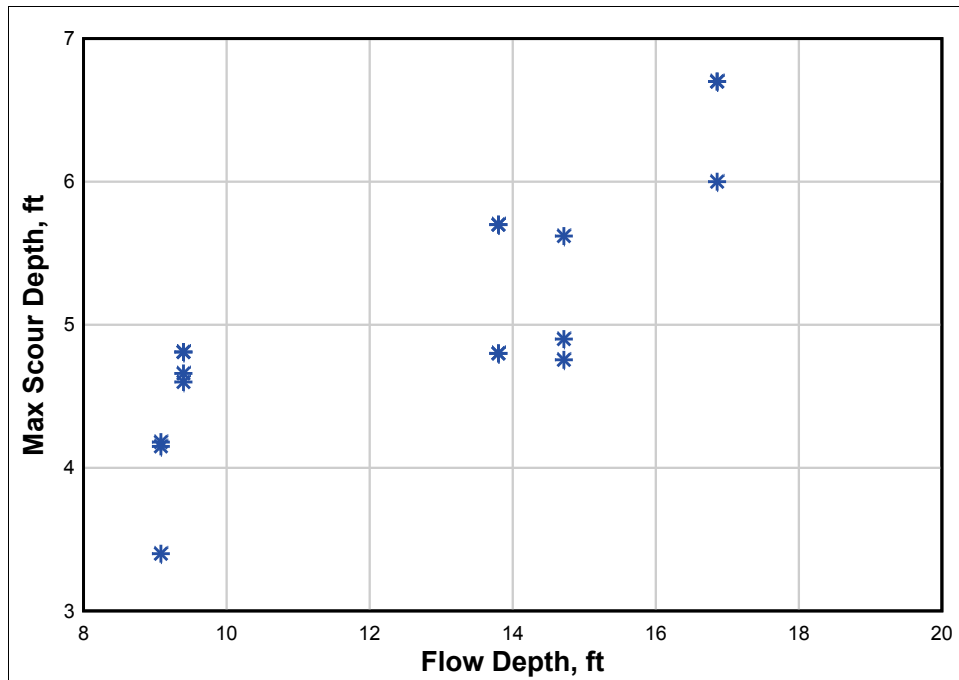


Figure 4. Scour depth for round pier test.

As with the round piers, a similar pattern of increasing scour depth with flow depth was shown with the BNSF bridge pier sets. Since multiple tests with the BNSF pier sets were not conducted, the pier sets are only used in demonstrating the application of the model scale factor ratio for local pier scour.

Within each test, the variations in scour depth at the different piers are attributed to two main factors. First, there were slight variations in the approach flow depth and that is reflected in the small discrepancy in unit discharge. Since scour depth is directly dependent on the approach flow depth (Figure 4), the variation can impact the final scour depth. Second, the test section was molded with an accuracy of +/- 0.5 ft from the assumed initial prototype elevation of 414 ft. For all scour depth measurements, 414 ft was used as the start elevation. Prior to running, the bed was surveyed adjacent to the piers but was not surveyed in the approach. If one pier started at a higher or lower approach bed elevation, then there would be a variation in the approach depth resulting in variations in scour depth.

**APPLICATION:** Two different methods were used to compute the scale factor. The first was application of the HEC-18 equation (Equation 1). With the HEC-18 equation, the scour depth was calculated based on the flow depth, Froude number, and pier geometry. Then, using the scour depths from the HEC-18 equation (7.3–8.6 ft) and the values measured in the tests (3.4–6.7 ft), a scale factor ( $S_f$ ) ratio was computed with Equation 2. The scale factor ratios ranged from 1.27–1.81 and are shown in Table 1.

$$\frac{Y_s}{a} = 2K_1 K_2 K_3 \left( \frac{D}{a} \right)^{0.35} Fr^{0.43} \quad (1)$$

$$S_f = \frac{Y_{s\text{HEC-18}}}{Y_{s\text{Scale Test}}} \quad (2)$$

Where  $Y_s$  is scour depth,  $a$  is pier width,  $D$  is flow depth,  $Fr$  is Froude number,  $K_1$  is a correction factor for pier nose shape,  $K_2$  is a correction factor for angle of attack, and  $K_3$  is a correction factor for bed condition (HEC-18 2012). The second method was based on literature data that are readily available and similar in application. Qualifiers for selected literature data included pier geometry, sand sediment (fine–course sand), flume tests, and hydraulic parameters. A total of 62 data points were applied with 23 in the correct Froude range as shown in Figure 5. All data were plotted nondimensionally with the ratio of scour depth to flow depth versus the Froude number as presented in Figure 5. A logarithmic regression was used for each data set. From the logarithmic equations, Equation 2 could be applied to calculate a scale factor (Equation 3). This provides individual scale factors over the range of all available data (Table 2). The maximum and minimum values for the scale factor are 1.77 and 0.323, respectively. The range verifies that the HEC Equation 18 values are reasonable. Thus, the scale factors from HEC Equation 18 formulation is applied as the model scale factor for local scour.

$$S_f = \frac{0.6803 \times \log(Fr) + 3.3135}{0.9082 \times \log(Fr) + 3.4396} \quad (3)$$

Once formulated, the application of the length scale ratio conversion factor for scour is the same as other scale conversion factors. The measured model scour depth is substituted into the equation, in the form of Equation 3 and shown in Table 2, yielding the range of prototype scour depths.

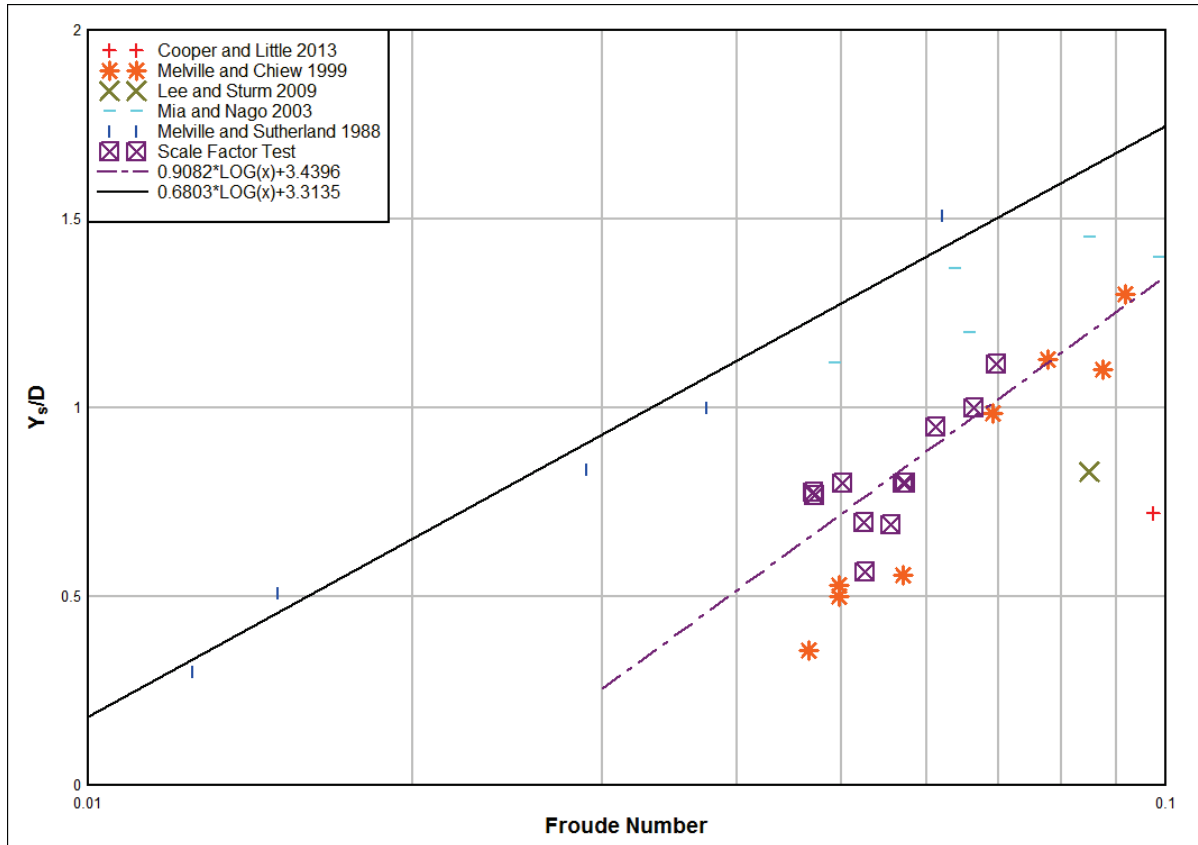


Figure 5. Literature data as compared to scale factor test data.

Table 2. Scale factors from Literature data and corresponding exponents.					
Froude Number	Scale Factor Ratio (Equation 2)				
	Melville and Sutherland 1988	Lee and Sturm 2009	Mia and Nago 2003	Melville and Chien 1999	Cooper et. al <sup>1</sup>
0.050	1.77	1.61	1.67	0.68	0.32
0.055	1.66	1.48	1.52	0.76	0.37
0.060	1.58	1.39	1.40	0.82	0.40
0.065	1.52	1.32	1.31	0.86	0.43
0.070	1.47	1.26	1.24	0.90	0.45
<b>Average</b>	1.602	1.413	1.431	0.802	0.395
<b>Standard Deviation</b>	0.121	0.138	0.170	0.085	0.051
<b>Maximum</b>	1.774	1.609	1.673	0.896	0.451
<b>Minimum</b>	1.468	1.261	1.244	0.681	0.323

<sup>1</sup> Cooper, D. R., C. D. Little, Jr., J. Cohen, B. Yuill, J. Wibowo, B. Robbins, R. Reed, M. K. Corcoran, and K. S. Holden. In publication. Application of bridge pier scour equations for large woody vegetation. ERDC Technical Report. U.S. Army Engineer Research and Development Center, Vicksburg, MS.

For implementation, the scale factor was applied to the scour depths measured from the pier sets (Table 3). The pier sets scoured less than that of the round piers as shown in Figure 6. This illustrates that the scale factor, by applying it to the measured values of the pier sets, produces a more conservative estimate of the maximum local scour depth.

<b>Table 3. Scaled and unscaled BNSF bridge pier set scour depths.</b>				
<b>Pier Set Scour and Scaled Scour Depths</b>				
	Flow Depth, ft	Scour Depth, ft	Calibrated Scour Depth, ft	
			SF = 1.81	SF = 1.27
<b>Test 3</b>	9.40	4.50	8.15	5.72
<b>Test 4</b>	13.80	5.00	9.05	6.35
<b>Test 5</b>	16.86	5.80	10.49	7.37

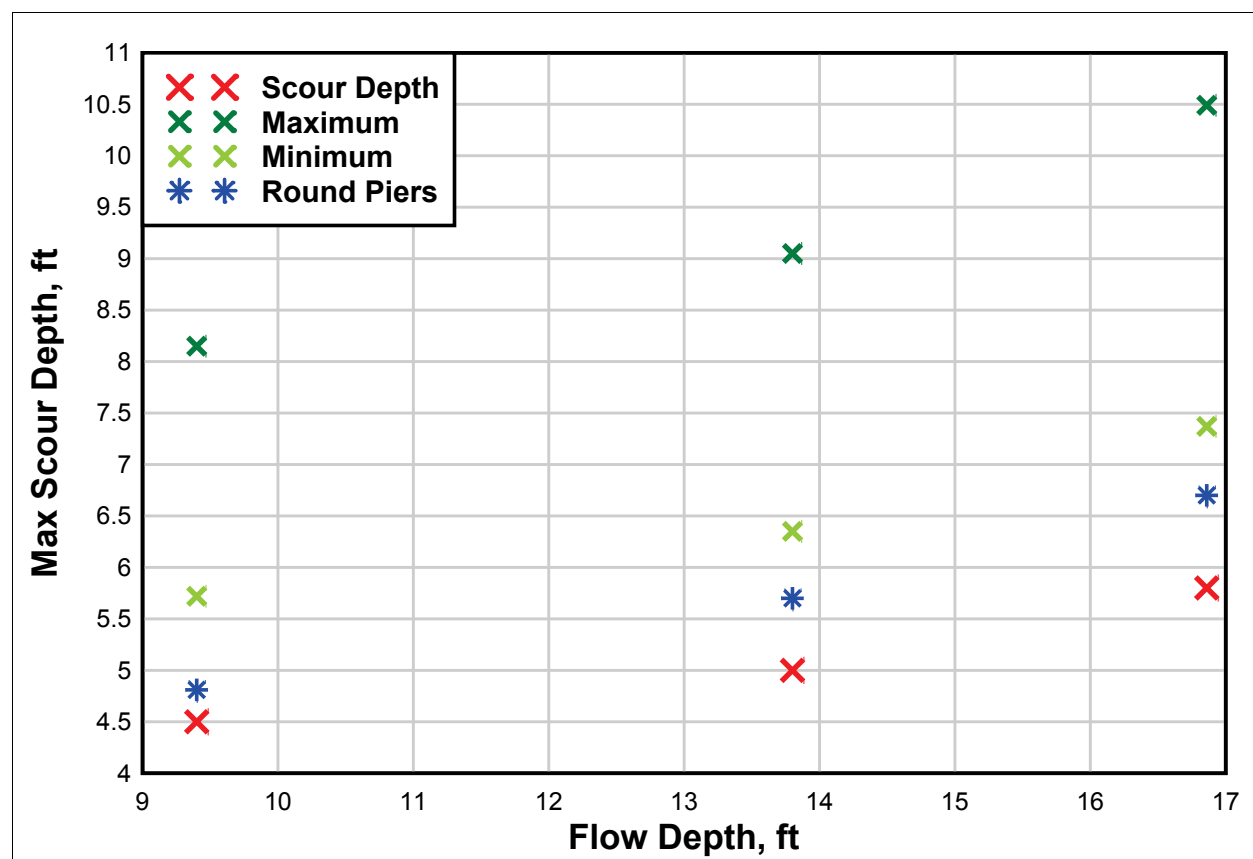


Figure 6. Scaled and un-scaled BNSF bridge pier set scour depths as compared to round piers

**RECOMMENDATION:** The scale factor as formulated here is intended only for the use at the BNSF bridge piers. Other locations with complex pier geometry would require a similar test to formulate a site-specific scale factor. The scale factor should be applied to the measured values from the general model to provide confidence that the estimated scour depths are slightly greater than what can be expected at the site. A conservative estimate of local scour depth provides a sufficiently deep protection plan for the pier footings to minimize the risk of potential undermining.



**ADDITIONAL INFORMATION:** This CHETN was prepared by Jeremy A. Sharp, Research Hydraulic Engineer at the U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this technical note can be addressed to Sharp at 601-634-4212 or [Jeremy.A.Sharp@usace.army.mil](mailto:Jeremy.A.Sharp@usace.army.mil).

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